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Manufacture: A Computer Aided
Advisor for the Manufacture of
Submarine Hulls**

**U.S. DEPARTMENT OF THE NAVY
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NAVAL SURFACE WARFARE CENTER**

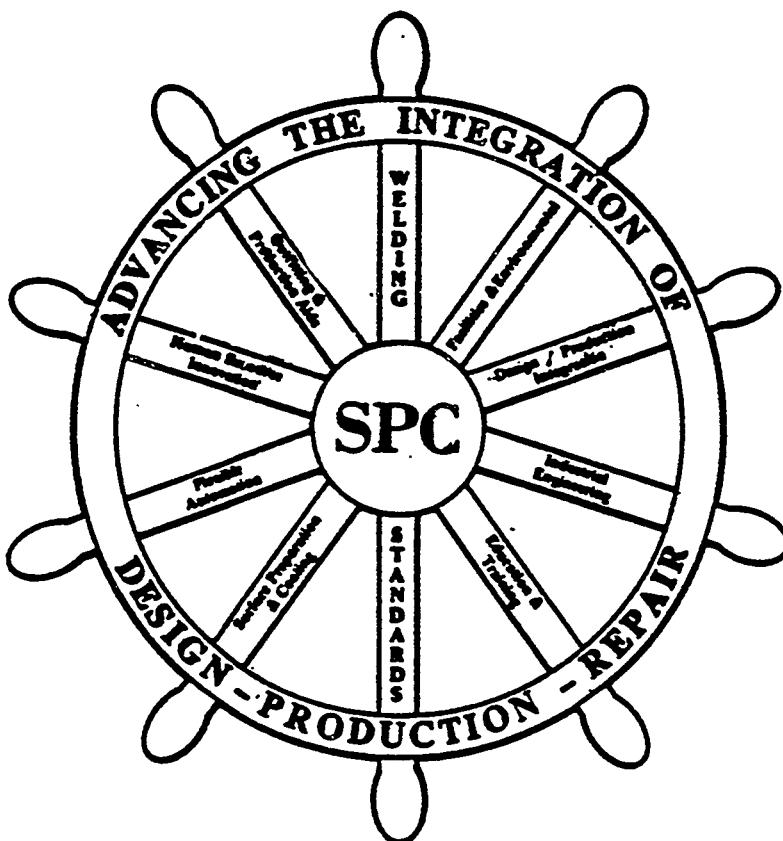
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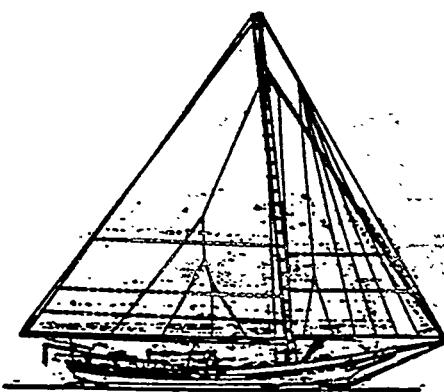
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No. AP

Design Through Manufacture: A Computer Aided Advisor for the Manufacture of Submarine Hulls

Harry West, Visitor and Mike Gallo, Visitor, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA

ABSTRACT

A computer graphics based advisory system has been developed to aid in the design and manufacture of submarine hulls. The design and manufacture advisor incorporates models of the materials (steel) and processes (bump forming, roll bending, welding, and fixturing) used for the manufacture of the hulls, and allows the user to explore the effect of different material qualities (described in terms of variances of thickness and yield strength), and different manufacturing parameters (punch penetration, punch spacing, and number of fixtures, for example) on the resulting quality (circuity) of the hull section. By "Designing through Manufacture" in this way the resulting design of the submarine hull section is not just a geometric representation of the desired shape of the hull, but incorporates explicit information about the materials and processes used to create the shape, and of the quality that results from the designer's choice of materials and processes.

INTRODUCITON

The design engineer is responsible not only for the fitness of the design for the function intended, but also for its cost and ease of manufacture. The designer cannot "throw the design over the wall" to manufacturing and hope that they will find a way to make the part to print, but must be responsible for designing the part to facilitate manufacture, and assembly.

Design engineers have to understand the manufacturing implications of design decisions. However, considerable experience is needed for a design engineer to gain such an understanding. Often the interaction between the design and the manufacture of the part is complex and product specific, and is a type of knowledge not generally featured in an engineering student's curriculum. Design engineers gain such knowledge on-the-job; by trial and error, and from more experienced coworkers or their supervisor. On-the-job training is expensive; there is a need for computer-aided-design tools to provide an alternative route for learning the complex details of how the design of a part affects its manufacture, and to enable less experienced designers to produce designs that are manufacturable.

There has been considerable interest in developing such manufacturing advisory systems [Jakiela and Papalambros 1985, Desa et al. 1987]. However, most of these developments have concentrated primarily on the purely geometric characteristics of the parts and their effect on the ease with which the parts can be assembled, without regard for the manufacturing process used to

produce the part itself. In this paper a Design through Manufacture (DTM) advisory system is described that provides the designer with explicit feedback of the interaction between the design of the part and the manufacturing process used to produce the part.

Design Through Manufacture

Conventional computer-aided-design tools allow the designer to create parts geometrically without explicit consideration of the manufacturing process used to produce the part. Some more recent developments in Computer-Aided Engineering (CAE) provide the designer with feedback of an estimated cost of the part based on the tolerance specified (Cognition 1988), but the costing is done after the geometric feature is designed.

The philosophical basis for Design through Manufacture is that the starting point for any design should be readily available materials, and that the designer should manufacture the part by performing a computer simulation of the manufacturing process. The designer cannot suppose the geometry of a part on the CAD screen, but must manufacture the geometry. Secondly, the models of the engineering materials and the manufacturing process should not be idealized, but be realistic representations of the materials and processes available. The computer simulation of the manufacturing process should perform the manufacturing operation on the computer with the same tolerance and 'quality' that would be expected on the factory floor. In this way the designer can visualize the effect of design decisions on the effort required to manufacture the part, and the effect of the manufacturing process on the cost and quality of the real part.

A computer model of a part designed through manufacture can include explicit descriptions of the "raw material" used in its manufacture, of how the part was manufactured, and its expected tolerances and quality. Because all information pertinent to the design and manufacture of the part is included in the description of the part, the effect of any changes in a design or manufacturing parameter on the subsequent stages of design and manufacture can be readily simulated.

There is a recognized need for incorporating interactive design aids into the design process, and many design engineers welcome intuitive tools that can aid their design process. [Zeid 1987, Grant 1987]. One of the earliest examples of a Design through Manufacture system was developed in 1975 [Gossard 1975], but the computational complexity of modelling real manufacturing processes has inhibited the continued development of such systems.

The Manufacture of a Submarine Hull Section

The example of the manufacture of a submarine hull has been chosen for the development of this Design through Manufacture system. The circular geometry simplifies the system. A simplified cartoon of the manufacturing process for a submarine hull is shown in Figure 1. The process can be divided into the following stages:

- Select steel
- Cut steel plate to size
- Bend plate into arc
- Fixture plates for assembly into circular hull section
- Assemble plates (weld)
- Fixture hull section for assembly with a second section to remove out-of-roundness
- Assemble hull sections (weld)

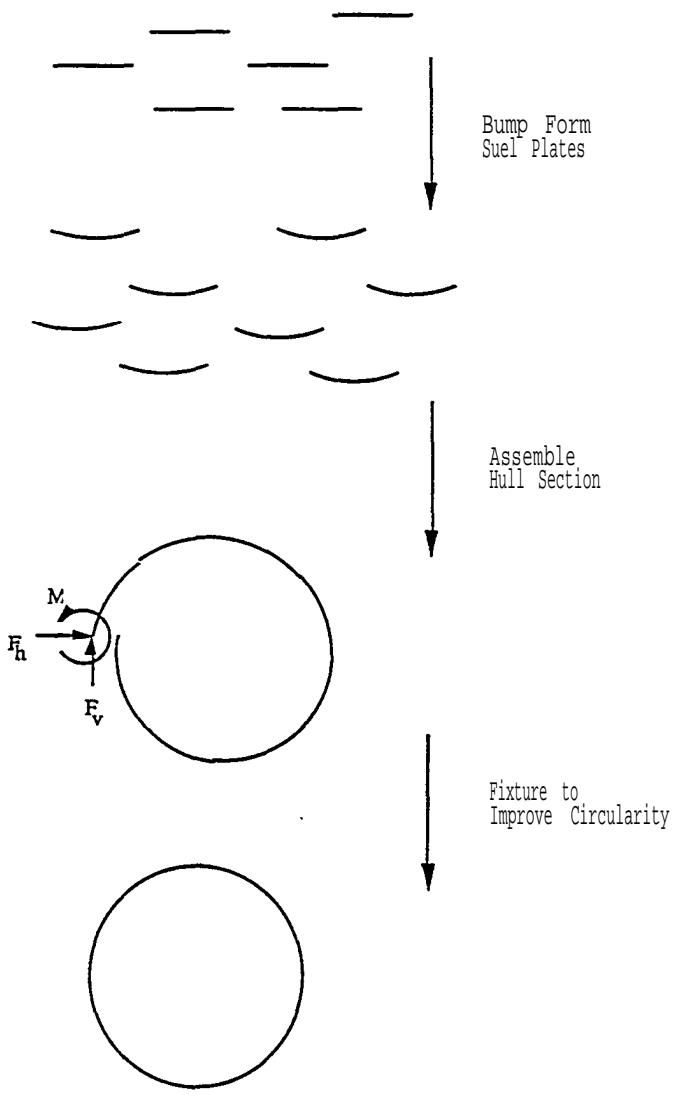


Figure 1: Sketch of Idealized Hull section .

The hull sections are manufactured from steel plates, HY-80 Armor Plate Steel [Alloy Digest 1966], supplied directly from the steel mill. Material properties of the

input stock can vary from plate to plate, and from point to point on the same plate. Properties such as grain structure, alloy content, and yield strength will vary due to process variances in the manufacture of the steel. Localized stress can result from the rolling mills and heat treatment of the plate. Flame and plasma cutting methods are used to cut plates to size. The heat input will relieve the residual stresses in the heat affected zone and may result in workpiece distortion. The amount of distortion depends on the residual stresses present in the workpiece, the variation in the amount of heat generated by the cutting heat source, and the rate of cooling of the workpiece after cutting.

The hull section of a submarine is circular, assembled from 8 curved steel plates. The steel plates are formed into arcs by bump forming or roll bending. Strain hardening, plate thickness, maximum moment point location, and machine geometry may vary and affect the resulting curvature. Sequential bending, also called bump forming, applies a three-point bending moment at discrete intervals along the length of the workpiece. A sketch is shown in Figure 2. The plate is placed on a stationary die, with a spacing of $2a$. The punch is displaced a distance Y_p , referred to as the punch penetration. When the punch is retracted, the plate will partially springback. This process is repeated at a series of points along the length of the plate and results in a finished shape that approximates a smooth curve. The mechanics of this process are discussed in [Hardt and Wright and Constantine 1989].

The United States Navy imposes strict requirements for the dimensional tolerances of submarine hull contours. A typical circularity tolerance for a submarine hull is approximately $\pm 1/2$ in. on a diameter of 42 feet. Circularit measurements are required at regular intervals along the pressure hull, and each point must be within the specified tolerance. A sketch of a hull section without stiffeners, is shown in Figure 3. Methods allowed by Navy specifications to take circularity measurements include the bridge gauge method, internal swing arm, internal radii, method of optical squares, the external template, and photogrammetry [Jacobson, 1985].

In addition to the Navy specified tolerances for final configuration, there are fit-up requirements for the assembly and welding of the hull segments. Excessive mismatch at the weld joint will require additional time and expense for fitting and fairing methods to be applied to allow proper welding. Problems encountered during the manufacturing of submarine hulls due to workpiece deviation from nominal include "chasing the bubble" while assembling two hull segments. As the weld progresses, the local mismatch is corrected by fitting and fairing methods. If there is an excessive mismatch between the two hull segments being joined, an uncorrectable "bubble" will develop that must be cut out before the assembly weld can be completed. Ideal manufacturing processes result in no residual stresses in the material, and yields dimensionally perfect parts, eliminating the need for fitting and fairing. Existing manufacturing capabilities do not allow this goal to be achieved.

SYSTEM OUTLINE

The Design through Manufacture advisor is a graphics based system developed using X-windows on a UNIX based VAXstation II with a black and white monitor. The programming is written in the "C" language, and comprises approximately 3000 lines of code and comments.

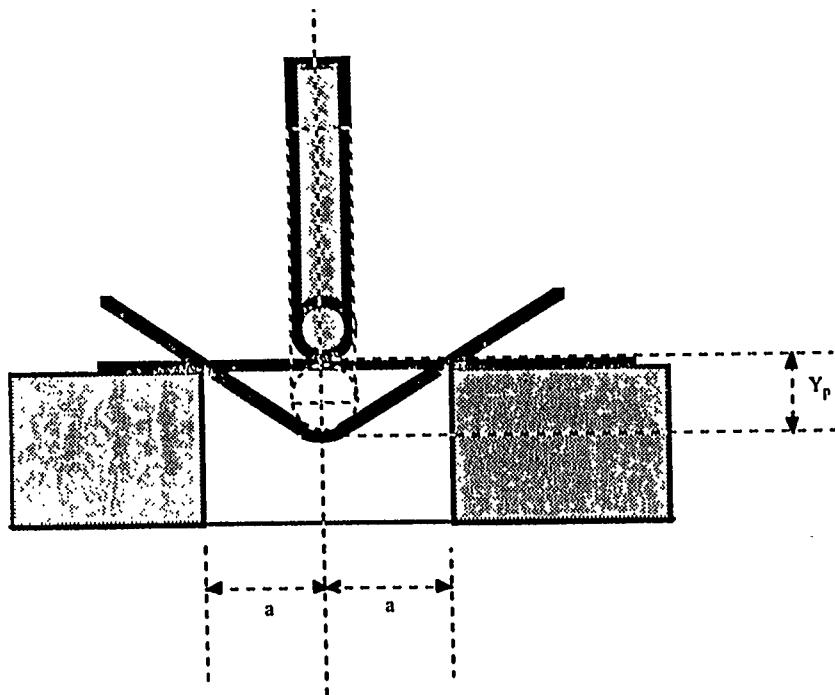


Figure 2: Bump Forming Geometry

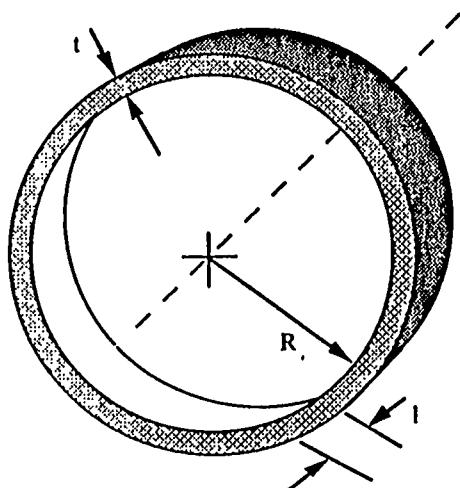


Figure 3: Sketch of a Submarine Hull Section

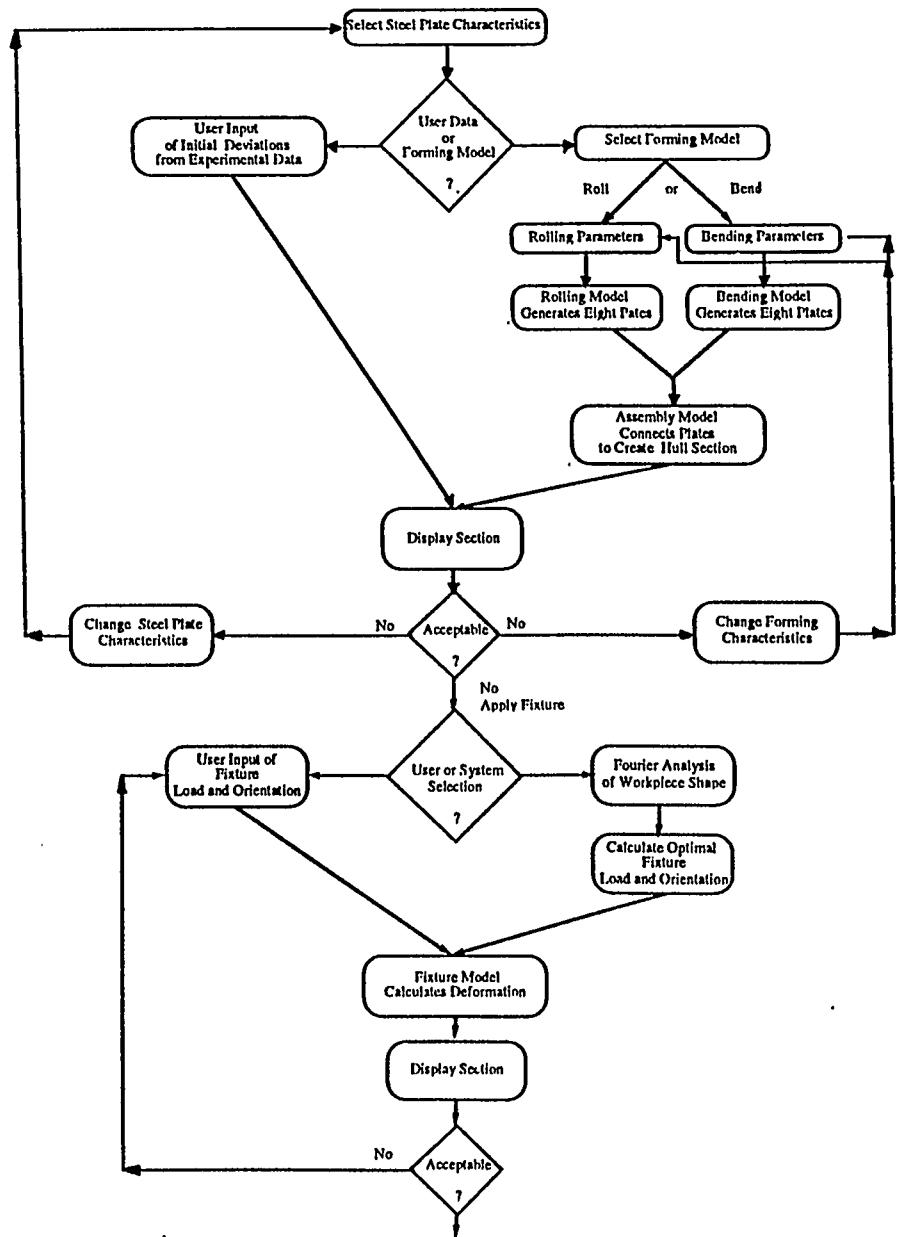


Figure 4: Overview of Manufacturing Advisor System

The system facilitates user interaction with the bending and rolling models developed by [Hardt, Wright and Constantine 1989], facilitates the display of experimental out-of-roundness data, and helps the user to design fixtures to improve the roundness of the submarine hull sections. An overview of the manufacturing advisor system is shown in Figure 4. The manufacturing advisor allows the design engineer to "experience", through computer simulations, the impact of design decisions on the manufacturing process, and to optimize manufacturing decisions based on the process models. Currently a simplified model of the hull assembly process is used that does not incorporate stiffening flanges.

The inputs to the system are the characteristics of the steel plate in terms of its geometry (thickness) and material properties (modulus of elasticity, yield strength, strain hardening behavior), and the expected tolerance in those characteristics. The geometry of a hull section can then be created either from experimental measurements or by using the rolling or bending models described in a companion paper [Hardt, Wright and Constantine 1989]. The geometry of the rolling or bending processes can be specified interactively by the user, as can the allowed variation in output (a measure of the quality control standard on the forming process). The output of the forming models is eight plates of different curvatures. The different plate shapes are generated by creating a stochastic distribution of steel plate characteristics that might be expected from the allowed tolerances in the specification of HY80, and propagating the effects of these characteristics through the forming process. Plates that exceed the quality control limits are rejected.

The eight plates are then assembled by butting them together so that their tangents match to give a smooth continuous curve, and then applying a combination of forces and moments to the last two free ends to complete a hull section. This process is sketched in Figure 1. As a result of the non-uniformity of the curvature of the eight plates the hull section is out of round.

The out-of-roundness of a hull section can be improved by changing the steel plate characteristics, by changing the forming parameters, or by applying a fixture. The steel plate specifications can be changed to allow a smaller variation in geometry or material characteristics. Alternatively, the forming processes can be modified so that variations in the steel plate characteristics result in smaller variations in the resulting curvature of the eight curved plates, or the quality control on the output of the forming process can be tightened so that only more uniform plates are assembled into hull sections.

The manufacturing advisor currently allows the user to design 2-, 3- and 4-point fixtures, or alternatively, the system will automatically generate a series of such fixtures to minimize the out-of-roundness of the hull section in the least squares sense. The out-of-roundness is described in terms of Fourier coefficients by treating it as a purely radial distortion. By matching Fourier coefficients of the out-of-round shape of the hull section to the Fourier coefficients of the deflections caused by applying different types of fixtures, the orientation and load of a set of fixtures is designed to optimize the resulting shape of the hull.

The plate assembly model and fixturing distortion models have been developed based on a simplified elastic analysis for small deflections. The models assume that the section radius is large compared to the thickness of the plates, that the deflections can be described as small

deviations from a circular geometry, negligible hoop stress, and that the maximum stress is below the yield point of the material.

The manufacturing advisor graphically displays in 2-D the hull segment's initial shape and the change in the shape due to fixturing. The design shape and allowable deviations are overlaid for comparison. An examples taken from an interactive session working with the fixturing model are shown in Figure 5.

SYSTEM DESCRIPTION

The manufacturing processes modeled are:

- 1 Bump forming of plates
- 1 Roll bending of plates
- 1 Assembly of plates into closed cylinder
- 1 Fixturing to reduce circularity errors

The design parameters that may be varied are given in Table 1

Table I: Design Parameters

1. The physical dimensions of the segment
 - a. Radius to midplane
 - b. Thickness of plate and variance
 - c. Axial length of segment
 - d. Contour limit
2. The material properties
 - a. Modulus of Elasticity
 - b. Yield strength and variance
 - c. Strain hardening modulus/Modulus of Elasticity ratio
3. The initial deviations from true geometry
4. The forming model parameters
 - a. Punch penetration
 - b. Machine geometry
 - c. Quality control on plate curvature
5. The fixture loading conditions
 - a. The angle relative to the vertical axis for future load application for each fixture
 - b. The load magnitude for each fixture

Forming of Plates

Forming models have been developed for bump forming [Hardt, Wright and Constantine 1988] and roll bending [Wright, 1988]. These models, based on given material properties, plate geometry, and machine geometry, predict the final shape of the formed plate. Statistical models of parameter variations are used as input for these models. Parameters are given a uniform probability distribution within the material specification. The resultant output is formed geometry that varies stochastically from the nominal geometry.

Assembly Model to Close Cylinder

A hull segment is assembled from 8 formed plates. The variations from desired geometry, given by the forming models, will result in deviations from a true circle after assembly. It is assumed that the plates are attached together such that the plates form a smooth, continuous curve. As shown in Figure 1, the variations in plate curvature will result in a gap between the free end of the first plate and the free end of the last plate.

To butt the two ends together tangentially, the force

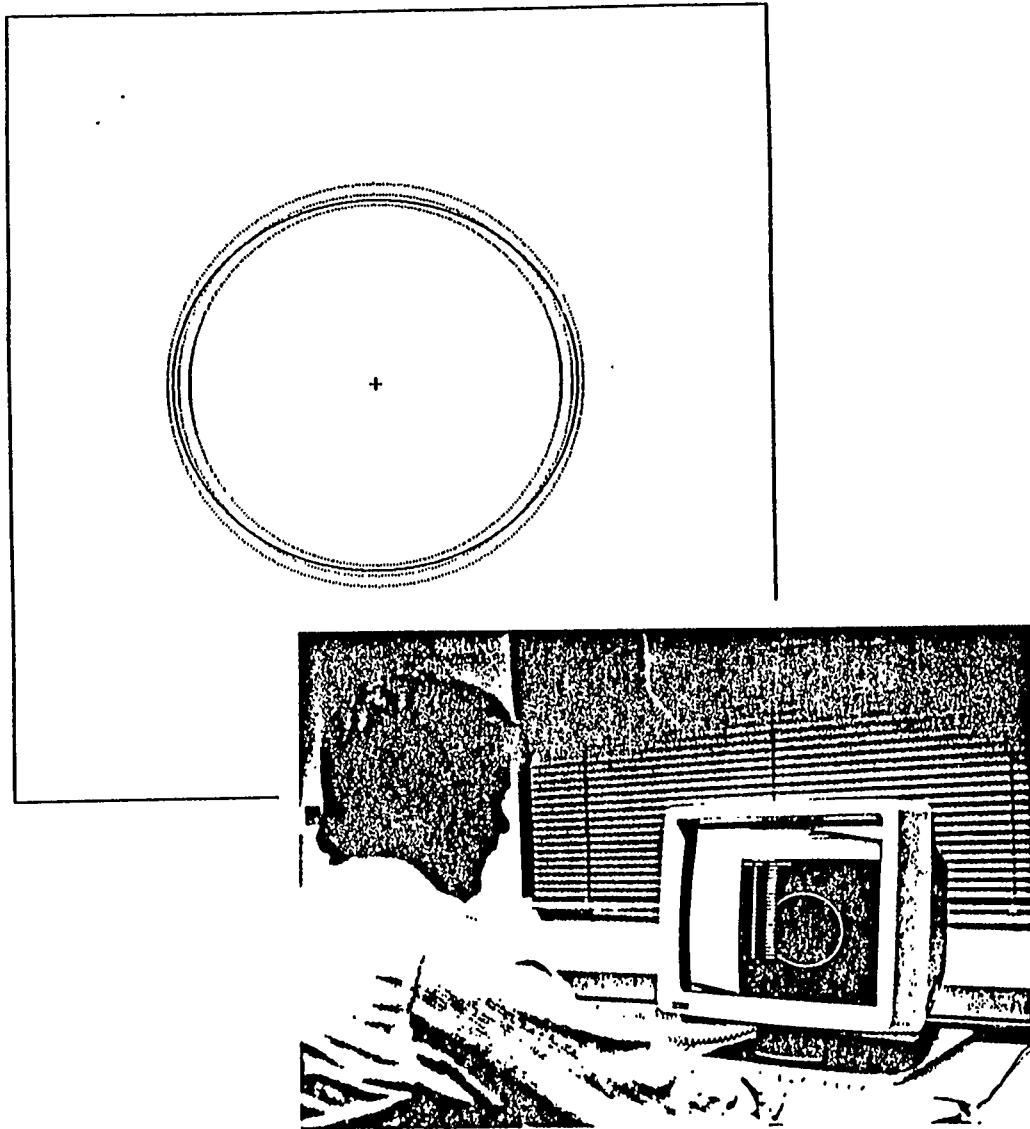


Figure 5: Examples of Interactive Session with Manufacturing Advisor

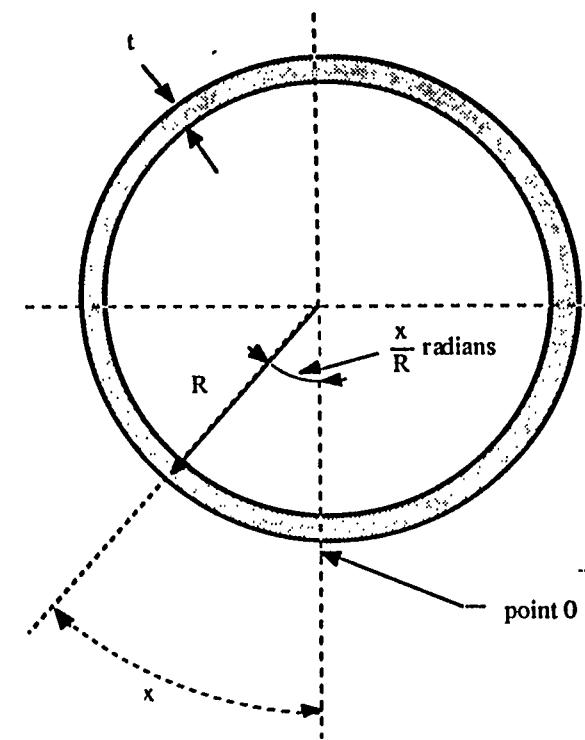


Figure: 6 Cylindrical Ring Hull Segment Model

components V and H , and the moment M_0 , shown in Figure 1, are applied to the ends. The radial gap, A_y , the tangential gap, A_x , and the angular mismatch, are derived in terms of the unknown force and moment components using Castigliano's Theorem [Roark, 1975]. These equations can then be solved for V , H , and M_0 .

The submarine hull segment is modelled as a cylindrical ring, as shown in Figure 6 below.

The distance circumferentially along the neutral plane of the plate from point 0 is described by x , R is the radius to the neutral plane of the plate, x/R is the angle, in radians, from the diametral line through point 0 to the point at distance x , and r is the thickness of the plate.

Assuming that the shape of the hull section can be modelled by small deviations from this idealized cylinder the forces and moments necessary to assemble the two free ends together can be calculated along with the resultant deflection of the hull section. The output of this part of the elastic model is a closed cylinder with known initial deviations, out-of-roundness, from the desired shape.

Applying Castigliano's Theorem [Gallo 1988], the radial force, l' , is given by:

$$V = \frac{\Delta y E I}{\pi R^3} \quad (1)$$

The tangential force, H , is given by:

$$H = \frac{E I}{(3\pi - 2) R^3} (\Delta x - \frac{\Delta \theta R}{\pi}) \quad (2)$$

and the applied moment, M , is given by:

$$M = \frac{\Delta \theta E I - 2\pi H R^2}{2\pi R} \quad (3)$$

The reactions V , H , and M_0 necessary to connect the two free ends are solved for using Equations [1], [2], and [3], and the resultant radial deflection is given by:

$$\begin{aligned} \frac{\partial U}{\partial V_0} = & \\ \frac{1}{EI} \{ & \left[\left(-M_0 R^2 - V R^3 \pi - H R^3 + \frac{H}{4} R^3 \right) \cos \left(\frac{x_0}{R} \right) \right. \\ & \left. + H R^3 \pi \sin \left(\frac{x_0}{R} \right) \right] - \left[-M_0 R^2 - H R^3 \right. \\ & \left. + \left(V R^2 \left(\frac{x_0}{2} - \frac{R}{4} \sin \left(\frac{2x_0}{R} \right) \right) \right. \right. \\ & \left. \left. + \frac{H}{4} R^3 \cos \left(\frac{2x_0}{R} \right) \right) \cos \left(\frac{x_0}{R} \right) \right] \\ & \left. + H R^2 \left(\frac{x_0}{2} + \frac{R}{4} \sin \left(\frac{2x_0}{R} \right) \right) \sin \left(\frac{x_0}{R} \right) \right] \} \end{aligned} \quad (4)$$

Fixturing for Assembly

Prior to welding two hull sections, the out-of-roundness of the hull section must be reduced. Fitting and fairing of

components for assembly may account for up to 25% of the fabrication costs of large structures [Moshaiov 1988]. Fitting and fairing aids are used to align mating, workplaces for proper welding fit-up. Fitting and fairing aids in common use in U.S. shipyards are described by Maciel 1984]. The devices modeled for application to submarine hull segment circular deviations are those capable of two-point diametral loading and three-point radial loading, such as hydraulic rams, come alongs, and push-pull jacks.

cylindrical structure under two-point diametral loading shown in Figure 7 below.

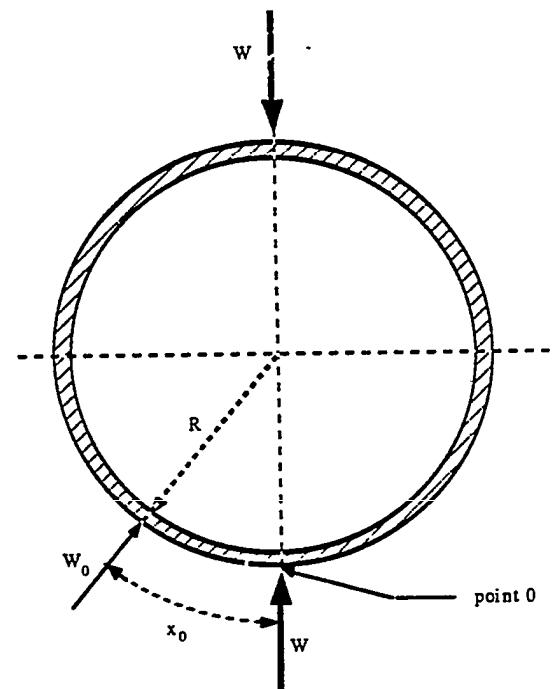


Figure 7: Two-point Diametral Loading

The radial deflection of each point x , is given by:

$$\begin{aligned} \frac{\partial U}{\partial W_0} = \frac{R^2 W}{EI} \left[& -\cos \left(\frac{x}{R} \right) \left(\frac{x}{R} - \frac{R}{4} \sin \left(\frac{2x}{R} \right) \right) - \frac{2}{\pi} \right. \\ & \left. + \left(\frac{R}{\pi} + \frac{R \pi}{8} \right) \cos \left(\frac{x}{R} \right) + \frac{R}{\pi} \sin \left(\frac{x}{R} \right) \right] \end{aligned} \quad (5)$$

Similar equations have been developed for three and four point loading [Gallo 1988].

Fourier Series Description of Fixture Loading

The deviation of the actual hull segment from the desired

shape can be described by the equation:

$$f(x) = r(x) - R \quad (6)$$

where $r(x)$ is the actual radius at circumferential point x , R is the nominal radius, and $f(x)$ is the deviation. For a closed circular hull segment, $f(x)$ will be periodic, and can be decomposed into its Fourier series components. If we assume that $f(x)$ is known for a discrete number of points, m , then the coefficients of the series can be evaluated numerically [Acton, 1970]:

$f(x)$ is given by:

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^N b_n \sin(n x) + \sum_{n=1}^{N-1} a_n \cos(n x) \quad (7)$$

The components a_k and b_k can be converted to their magnitude and phase components; the magnitude component is given by:

$$c_k = \sqrt{(a_k)^2 + (b_k)^2} \quad (8)$$

The phase component is given by:

$$\phi_k = \tan^{-1} \left(\frac{b_k}{a_k} \right) \quad (9)$$

The Fourier Series Decomposition for two-point fixture loading is shown in Table 2. The fundamental, the component with n equal to the number of fixture points, is significantly larger than the other components:

Table 2: Fourier Series Decomposition for a Two-point Fixture

Number (n)	C_n (in.)	f_n (Deg)
0	3.4×10^{-5}	0.0
1	-3.6×10^{-17}	1.94
2	-7.2×10^{-4}	-0.656
3	-1.6×10^{-16}	-2.512
4	-5.5×10^{-5}	-1.311

To demonstrate the Fourier decomposition, a hull segment is analysed with initial deviations from a nominal radius of 192 in., as shown in Table 3. A smooth curve has been fitted through these points with the Cardinal Spline Formulation.

Table 3: Initial Deviations of Hull Segment

Angle (Deg.)	Initial Dev. (in.)
0	-1.0
45	0.0
90	1.0
135	0.0
180	-1.0
225	0.0
270	1.0
315	0.0

The result of the Fourier Series Decomposition of these initial deviations is shown in Table 4:

Table 4: Fourier Series Decomposition of Out-of-Roundness

Number (n)	C_n (in.)	f_n (Deg)
0	1.9×10^2	0.0
1	1.0×10^{-2}	18.1
2	1.0×10^0	-0.6
3	1.9×10^{-2}	53.8
4	1.7×10^{-1}	71.4

In order to compensate for a given out-of-roundness Fourier series component, a fixture must be chosen that has a significant component of the same period, and oriented so that the phase angle of the fixture Fourier series component at the desired period matches the phase angle of the out-of-roundness Fourier series component. The fundamental of the Fourier series components is much larger than the other components so the effect of the fixture loading can be approximated as:

$$\begin{bmatrix} D_1 & 0 & 0 & 0 \\ 0 & D_2 & 0 & 0 \\ 0 & 0 & D_3 & 0 \\ 0 & 0 & 0 & D_4 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ W_4 \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} \quad (10)$$

where D_i is the magnitude of the fundamental of the Fourier series component for a unit fixture load, and W_i is the fixture load. The magnitudes of the fundamentals of the Fourier components for two-, three-, and four-point fixtures are given in Table 5:

Table 5: Magnitude of Fundamental Fourier Series Components

Component	Magnitude
D_2	7.2×10^{-4}
D_3	2.1×10^{-4}
D_4	1.1×10^{-4}

The fixture loading, W_i , can be calculated directly by inverting equation (12). For the example shown in Tables 3 and 4, the optimal fixture loading is:

Table 6: Calculated Fixture Loading

Fixture Type	Angle (Deg)	Load (lbs)
Two-point	-0.3	-1413.25
Three-point	17.9	-88.606
Four-point	17.8	155.031

If the fixture loading shown in Table 6 is applied to the hull segment with initial deviations as shown in Table 3, the resulting final deviations from nominal radius are shown in Table 7, which are within spec.

Table 7: Final Deviations of Hull Segment

Angle (Deg.)	Final Deviation (in.)
0.	-0.07
45.	-0.13
90.	0.15
135.	-0.10
180.	-0.03
225.	-0.10
270.	0.13

USER INTERFACE

The interactive graphics program is to be used as an analysis tool by design engineers to determine the effect of design decisions on the manufacturing process. The design parameters that maybe changed have been listed in Table I.

The program graphically outputs the resulting deflections of the workpiece as each design change is made, allowing immediate evaluation of the change's impact. The workpiece's geometry is graphically displayed by exaggerating the out-of-roundness errors so that they can be readily perceived by the designer, and the contour limits are plotted on the same scale to allow comparison with the design tolerances, as shown in Figure 8.

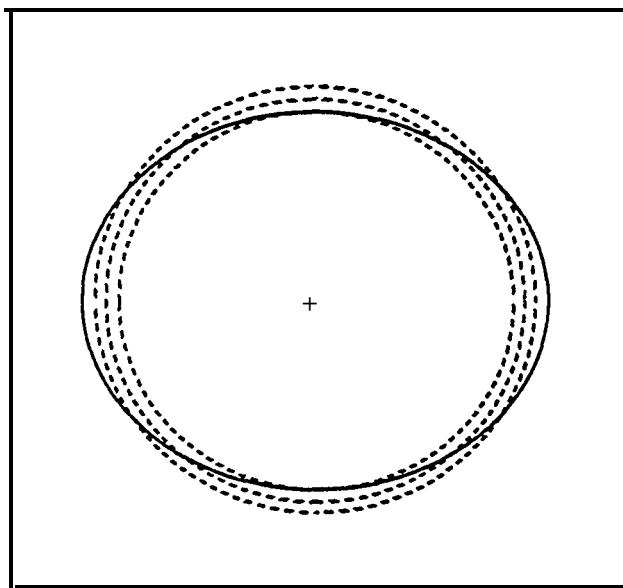


Figure 8: Graphical Display of Initial Deviations

The program is designed to be interactive with the user, and will prompt the user to make key decisions. The program is menu driven, and displays a menu listing several choices. The choices will either 1) lead to a submenu 2) perform a desired function or 3) go back to a higher level menu. The user selects the desired option by placing the mouse cursor in the box adjacent to the choice and pressing any button on the mouse.

Changing any design parameter will cause the program to recalculate the new shape of the hull section using the existing fixture loading conditions and graphically display the results. To view the numerical values of the final deflection, the user chooses the "Display Final Deflections" option from the "Main Menu". The program will then overlay the numerical values on top of the graphical display, as shown in Figure 9.

CONCLUSIONS

A computer graphics based advisory system has been developed to aid in the design and manufacture of submarine hulls. By "Designing through Manufacture" in this way the resulting design of the submarine hull section is not just a geometric representation of the desired shape of the hull, but incorporates explicit information about the materials and processes used to

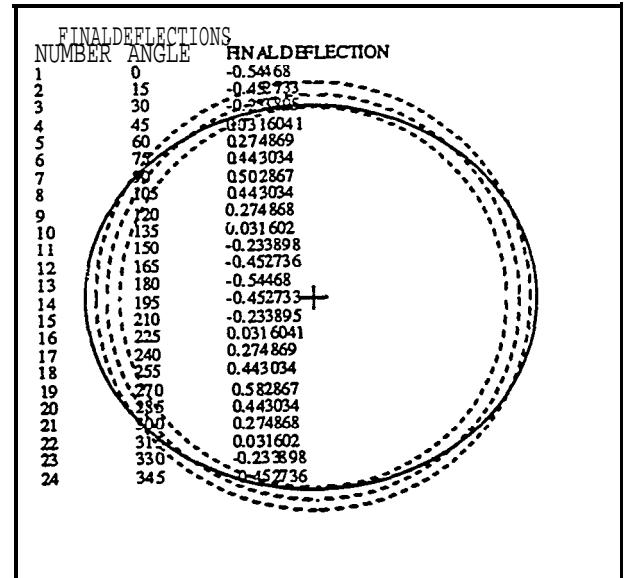


Figure 9: Display of Final Deflections

create the shape, and of the quality, as measured by the out-of-roundness of the hull, that results from the designer's choice of materials and processes. The interactive graphics program provides a convenient tool for the design engineer to analyze the impact of his or her decisions on the manufacturing process. By using this tool, potential problems faced by the manufacturer can be recognized at the design stage, and may be ameliorated by selecting alternative materials or processes. TM advantages of Design through Manufacture are:

- It is not possible to design parts that cannot be manufactured
- The designer understands the effect of his design decisions on the manufacture of the part and on its quality
- The designer can be assisted by the computer to explore different design and manufacture options
- The effects of materials and processes on tolerances are explicit
- The cost of the design can be made explicit

The system that has been developed is an incomplete prototype, and does not include all materials or process that the designer might consider. In particular, it does not include models of flame-cutting or welding processes. As an incomplete system it limits the freedom of the designer and may give misleading results.

Future development is directed at incorporating more materials and processes into the system but is limited by the lack of available process models. To be useful as a design aid process models must be sufficiently faithful to the process to provide meaningful results, and yet run sufficiently quickly that they can be used interactively. The development of fast process models is an area of current research [Eager and Moshavov 1988]

An important use of Design through Manufacture systems will be in education. The problem in design education is feedback working interactively with a DTM system is a way for design engineers to accelerate their learning experience, allowing the designer to make mistakes with silicon instead of steel.

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